3. Hurricanes and their Effects on Coral Reefs

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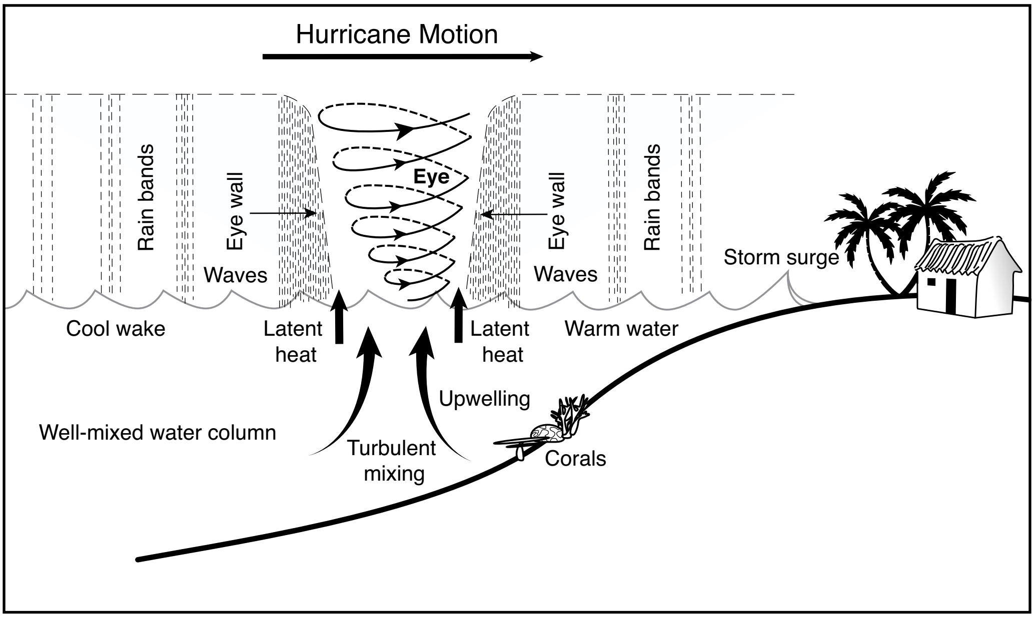
Background to Hurricanes

A hurricane (also tropical cyclone, typhoon) is a warm-core, low-pressure system that develops over tropical or subtropical waters. Most hurricanes form from a trough of low-pressure, over ocean surface temperatures greater than 26°C. As air moves across the ocean surface, it extracts moisture (water vapour) and energy (as a result of evaporation) from the ocean. The low pressure draws air inward, causing the water vapour to rise, cooling as it rises. When the vapour condenses to form clouds, it transfers the heat energy to the surrounding air. As the warm air rises higher in the atmosphere, it lowers the pressure at the ocean surface. This causes more air to enter at the ocean surface, which creates stronger winds and continues to transfer heat from the ocean into the atmosphere. As long as the atmospheric conditions are favourable and the ocean can provide the energy, this creates a feedback mechanism to strengthen the hurricane.

When fully-formed, hurricanes are well organised with a calm eye at the centre surrounded by an eye-wall where the strongest winds and most of the ocean heat extraction occurs, as illustrated in the figure below. Several rain bands can encircle the eye, also extracting smaller amounts of heat from the ocean. As a hurricane moves, it typically leaves a cool wake behind it (see ref. 3.) and pushes waves out in all directions. If a hurricane approaches land, these waves steepen and water piles up in the shallows, often pushing up onto the land. This phenomenon is called a storm surge and can be particularly damaging if it occurs during high tide. The greatest surge is usually generated in front of and to the right of a northern hemisphere hurricane (left front quadrant in the southern hemisphere).



This diagram illustrates how a hurricane forms over warm ocean waters and starts spinning in a counter-clockwise direction in the Northern Hemisphere. Large storm waves may result in significant coral reef damage. However, a hurricane will also cool surface waters and can often mitigate coral bleaching.

While there is a minimum ocean surface temperature for hurricanes to form, the energy that drives a hurricane is supplied by the upper section of the water column, not just the surface. Hurricane intensity is more closely linked to the ocean heat content than to surface temperature alone (4.). Once the eye of a hurricane moves over land it experiences greater friction and loses its source of moisture and heat, causing it to weaken. Hurricanes can also weaken at sea if their energy source is reduced by encountering cool waters (fronts, upwellings), or their vortex development is inhibited by entering a zone of high vertical wind shear.

Hurricanes help to regulate the earth's temperature, extracting heat from the ocean and redistributing it into the atmosphere; thereby moving tropical heat poleward. In the absence of regular hurricanes, tropical oceans retain more heat, which can then lead to larger, more intense hurricanes. Recent increases in ocean temperatures, very likely due to human-induced climate change, have seen tropical storms becoming stronger but not necessarily increasing in number (7. and Executive Summary p. 14).

Globally averaged land and ocean temperatures in 2005 were the highest on record according to NOAA and NASA analyses, with temperatures slightly warmer than in 1998. The 2005 hurricane season in the Atlantic and Caribbean was unprecedented, experiencing more than twice the annual average of named tropical storms over the past century and the greatest number of hurricanes in recorded history. While some of this may be attributed to improvements in hurricane observation skills through satellites and other instruments, there can be no doubt that 2005 was an extreme year for storm activity.

Hurricanes are classified by their wind speed in the well-known Saffir-Simpson scale. Category 1 storms have sustained wind speeds greater than 64 knots (33 m/s) and generally cause only minor damage upon landfall; Category 5 hurricane winds exceed 135 knots (69 m/s) and can devastate structures with both winds and storm surge.

Hurricane Category	Impacts
1	Wind 64-82 knots, storm surge 1.0-1.6 m, no real damage to building structures, damage to trees
2	Wind 83-95 knots, storm surge 1.7-2.5 m, some roofing and window damage, considerable damage to trees
3	Wind 96-113 knots, storm surge 2.6-3.8 m, some building damage, large trees blown down
4	Wind 114-135 knots, storm surge 3.9-5.5 m, complete removal of some roofs, extensive window damage, most trees blown down
5	Wind 136+ knots, buildings fall over, storm surge 5.6+ m, widespread loss of roofs, some buildings destroyed, all trees blown down

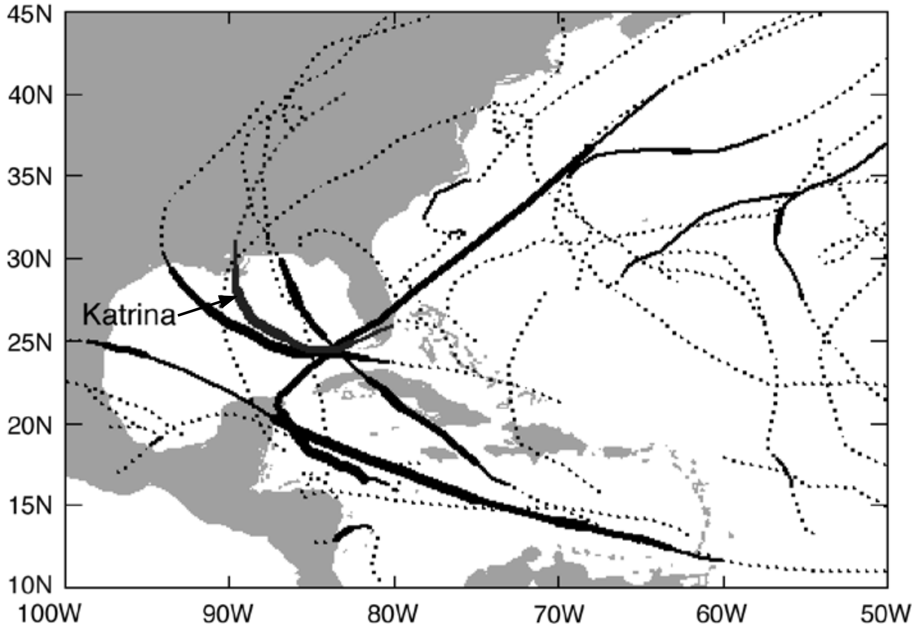
(a wind speed of 100 knots = 185.2 km per hour = 51.4 metres per second)

So Why was 2005 so Active?

Several factors are involved. There was an extensive region across the equatorial Atlantic where the vertical wind shear (the change in wind speed with height) was unusually low. Vertical wind shear interferes with the vertical structure of a hurricane and inhibits hurricane formation. The rate of latent heat exchange (the transfer of water vapour energy from ocean to atmosphere) was 20% greater than the largest value in the previous 25-year period and, therefore, strongly favoured hurricane activity. Record warm surface temperatures across the Gulf of Mexico, Caribbean and tropical Atlantic provided the energy source to form and sustain hurricanes. Sea-level pressure was exceptionally low across the Caribbean, again aiding hurricane formation (5.).

Many of these factors have been linked to climate-scale variabilities. Perhaps the most well-known of these is the El Niño-Southern Oscillation (ENSO); however, during 2005 conditions were ENSO neutral for most of the year. Other large-scale variabilities that have been linked to observed oceanic and atmospheric conditions include the Atlantic Multi-decadal Oscillation, the North Atlantic Oscillation and the Madden-Julian (40-day) Oscillation. It was the juxtaposition and magnitude of these causal factors that likely induced the record activity during the 2005 hurricane season. The effect of these was exacerbated by climate change, the largest contributor to the warm temperatures in the tropical Atlantic. Of the 0.9°C tropical Atlantic temperature anomaly (compared with a 1901-1970 baseline), 0.2°C was attributable to the weak 2004-05 El Niño; less than 0.1°C was attributable to the Atlantic Multi-decadal Oscillation; and most of the anomaly (0.45°C) was attributable to climate change (6.).

A side-note to the extreme nature of the 2005 season is that none of the named storms traversed Puerto Rico and the Lesser Antilles (Windward and Leeward Islands). Despite the very warm ocean surface temperatures, each of the Atlantic hurricanes passed around this region. While this absence of storm activity saved the island communities from the potential devastation of hurricane landfall, it also removed the ameliorating effects that tropical storms have for tropical regions.



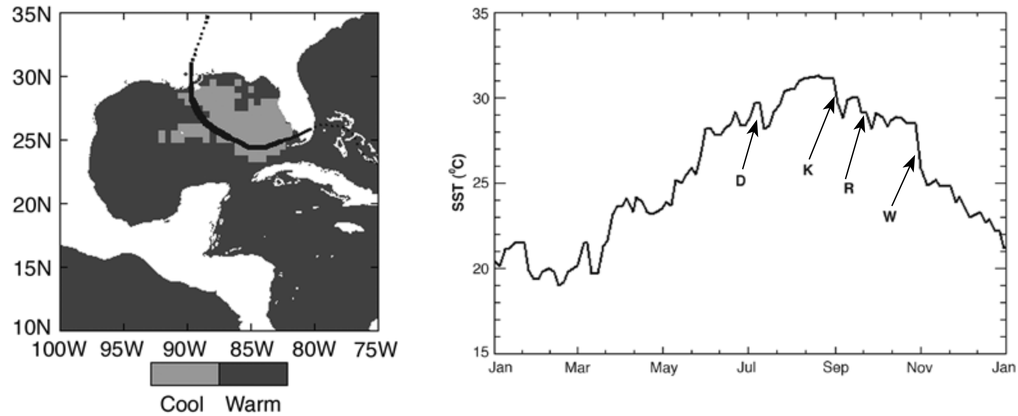
This figure illustrates the named storm tracks (including hurricanes) for 2005. Dotted lines show paths of tropical storms; hurricane strength is shown by the thickness of the solid lines (3 groups: categories 1; 2 & 3 together, 4 & 5 together). The marked track is of Hurricane Katrina whose storm surge devastated New Orleans. Note the clear region centred around 65°W:20°N; no hurricanes passed over the very warm waters, which resulted in massive coral bleaching in the Lesser Antilles . Compare this 'hole' with the NOAA thermal stress images on the front cover and on pages 9-11.

The Good and the Evil of Hurricanes for Coral Reefs

While there is often a perspective that hurricanes are only destructive and disastrous events, they also provide ecological benefits to tropical and sub-tropical environments. Rainfall gives a boost to wetlands and flushes out lagoons, removing waste and weeds. Hurricane winds and waves move sediment from bays into marsh areas, revitalising nutrient supplies. While there is always the potential for mechanical damage, coral reefs can also receive benefit from hurricanes during the warm summer months (1.).

During the summer hurricane season, as ocean surface waters become warmer, corals often experience thermal stress. Hurricanes can alleviate this thermal stress by three mechanisms. First, as hurricanes absorb energy from surface waters through the transfer of latent heat, the temperature of the water is reduced (evaporative cooling). The magnitude of the cooling is related to the intensity and extent of the hurricane. Second, hurricanes also reduce sea surface temperatures (SST) by inducing local upwelling, bringing deeper, cooler water to the surface. The amount of surface cooling resulting from these mixing mechanisms will depend on the hurricane wind speed and how the water temperature varies with depth at each location. Finally, the clouds of a hurricane shade the ocean surface from solar heating allowing the water to cool and reducing light stress.

The figure on the left shows regions of positive and negative sea surface temperature anomaly with the track of Hurricane Katrina over the cool wake. The graph on the right is a SST time-series at Sombrero Reef, Florida Keys showing the rapid drop in temperature following the passage of hurricanes Dennis (D), Katrina (K), Rita (R) and Wilma (W). Hurricane Katrina passed over the Florida Keys as a Category 1 hurricane on 26 Aug 2005, during the hottest period, reducing the temperature



stress and halting a temperature trajectory towards coral bleaching.

While larger, more intense hurricanes provide the greatest cooling near the ocean surface, they are also the most destructive. Waves and water movement significantly influence the structure and distribution of coral assemblages. Generally, the more delicate ‘branching’ corals (e.g. *Acropora* spp.) are more vulnerable to wave damage than corals with a ‘massive’ or ‘boulder-like’ growth form (e.g. *Porites* spp.). As a consequence, massive corals tend to dominate coral communities in areas regularly exposed to oceanic swells, while delicate species thrive in low energy areas such as lagoons and back-reef areas (2.). In addition, waves and tidal water movements scour some areas exposing the solid limestone structure of the reef, which provides a firm foundation on which corals can settle and grow. In other areas, water movement results in the accumulation of sediment and rubble, which is unstable and, therefore, less suitable for coral settlement.

The waves generated by hurricanes are larger and more powerful than those experienced under normal conditions and can affect all parts of a reef. As a consequence, they are the primary cause of hurricane-related damage to corals and coral reefs, often breaking coral branches and overturning colonies. Dislodged coral pieces can cause further damage as they are propelled onto other parts of the reef. In 2005, Hurricane Rita damaged the deep reefs of the Flower Garden Banks, while Wilma scoured the reefs of the Florida Keys.

Recovery from hurricane damage is variable. Often, branching corals recover quickly because of their rapid growth, and broken branches can even begin to regrow in new areas. However, recovery can be hindered by the accumulation and movement of coral rubble generated by the hurricane, and by increases in the abundance of algae, which compete for space within the reef. Terrestrial runoff resulting from heavy rainfall can also influence the nearshore reef ecosystems, smothering corals with sediment and other debris, as well as increasing nutrients (including those in fertilisers) that influence growth rates of algae, and lowering salinity, which can stress corals.

Conclusions

The influence of hurricanes on coral reefs can be beneficial and detrimental. Small hurricanes can provide fast relief during periods of thermal stress, whereas waves from large hurricanes can reduce a reef to rubble. Coral reefs have experienced these effects of hurricanes and survived for millions of years; however, in light of the rapidly changing climate, the ability of corals to recover from severe storms, while facing the combined effects of increasing thermal stress and ocean acidification, could be extinguished.

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